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DESIGN FEATURES OF SUPERCONDUCTING TRANSPORT AND ANALYSIS MAGNETS*

R. W. Fast and J. R. Heim

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R. W. Fast and J. R. Heim
National Accelerator Laboratory
Batavia, Illinois 60510

The design features of a 2.0 kG/cm cold iron beam transport quadrupole and of a 18 kG, wide aperture particle analysis dipole are given. Operating currents of 250 and 350 amps, respectively, were chosen, corresponding to conductor current densities of 19.7 and 27.6 kA/cm^2. Coil construction provides good conductor cooling and supports the large electromagnetic forces. Rectangular cryostats to provide a large LHe volume above the coil have been used and have proven to be both inexpensive to construct and of low heat leak. A column support capable of reacting large loads to room temperature with negligible heat leak has been used.

The superconducting magnets considered for use at NAL are either dipoles and quadrupoles operated DC for use as secondary beam transport elements or large dipoles serving DC as reaction particle analysis magnets. Since NAL secondary beam lines are quite long for other reasons, transport elements need not exceed 20 kG. The large volume analysis magnets operate at 18 kG or less. At these fields the use of iron is dictated to shape the field, either dipole or quadrupole, and to reduce the excitation required. Refrigerating the iron to 4.2° K facilities the design of compact, low heat load transport magnets, however, because of their large size, analysis magnet iron remains warm. Two magnets now under test at NAL are typical of these two general types. A 2.0 kG/cm iron quadrupole with a 10 cm diameter aperture 3 m long is currently being tested. The field is shaped by iron poles at 4.2° K. The stored energy at design gradient is ∿ 30 kJ. A particle analysis dipole with picture frame iron was tested in March, 1972. It has a useful aperture 0.2 m gap x 0.6 m wide x 1.8 m long, a field volume of 0.22 m^3. At the design field of 18 kG the stored energy is ∿ 600 kJ.

For superconducting magnets not operating in the persistent mode, and ours do not, current lead losses should be considered when choosing an operating current. The conductors leading into the helium vessel will be the major source of 4.2° K heat leak for high current magnet designs. Since overall magnet system efficiency is related to the heat leak, lower operating currents are desirable. Smaller conductor sizes corresponding to low current operation are also easier to wind into three-dimensional coil shapes. Therefore, we have decided to limit the operating current in our magnets to a maximum of 350 A, and choose lower currents whenever possible. The inductance of large coils designed for these operating currents will be 10 to 20 H. Power supplies with 10 volts output are adequate to charge analysis magnets with stored energies up to at least 1,000 kJ in about 20 minutes, which is satisfactory for most high-energy physics applications. With almost any iron/superconducting magnet the cost of the superconductor is a small fraction, seldom more than 10% of the total magnet cost. For this reason, there is no need to demand high current densities of the superconducting material. We have set as an upper limit conductor current densities of 20 to 30 kA/cm^2 at 20 kG.

A conductor which has performed well for us is 1.27 mm diameter round wire. The conductor would have a copper/superconductor ratio of greater than 2, would contain at least 50 Nb-Ti filaments and be twisted about one turn per cm. The short sample rating at 20 kG would be greater than 750 A. Operating this conductor at 250 to 300 A with good cooling results in a fully stable coil.

To insure predictable, reliable magnet operation the overall coil current densities should be kept as low as possible. We have found that overall current densities of 5 to 6 kA/cm^2 result in coils that are adequately compact for our designs. Also, reliable magnet operation can be achieved only by allowing no turn to turn, layer to layer, or coil to ground shorts. All the conductor we use is insulated with Formvar to NEMA specifications for additional protection. At slow changing rates the performance of the wire is unaffected by the thermal insulation provided by the Formvar.

Our coil construction concept is shown in Fig. 1. The epoxy glass laminate insulating spacers accurately position and rigidly support each turn.

The finished coil is then securely clamped to the cold iron or helium vessel wall. Electromagnetic forces developed in the coil structure during operation are transmitted through the insulating spacers and into the coil support structure. Where cold iron is used the magnetic forces are reacted directly in the cold iron. For warm iron magnets the forces must be reacted by the helium vessel. For example, the two-meter side of the analysis magnet coil experiences a total force of about 50 metric tons directed toward the room temperature iron yoke. These large magnetic loads are reacted by tension straps which tie the two-meter sides of the helium vessel together.

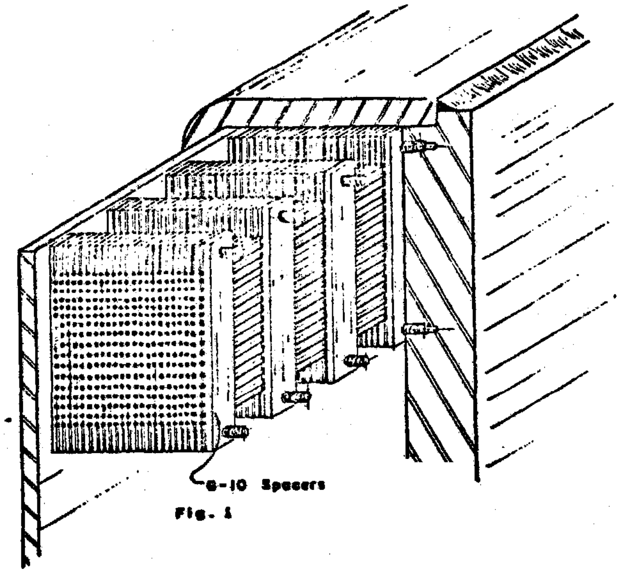

Fig. 1

Analysis magnet coil structure

Gas cooled current leads to carry 250 to 300 A can be quite small and for convenience we install both leads in a common tube. Figure 2 shows a typical lead, the number of braids[1] depending on the current desired. We size our leads predicated upon taking all of the cryostat boil-off of 2 to 3 liters/hr out the lead.

Supplying liquid helium to a magnet is far less sophisticated and more reliable if the cryostat has a low helium boil-off and large liquid helium volume above the coil. This requirement dictates the use of a liquid nitrogen cooled shield and multilayer insulation. A rectangular helium box allows for sizable liquid storage without enlarging the lateral dimension. We have found no difficulty in fabricating rectangular cryostats by welding flat plates. Figure 3 shows the

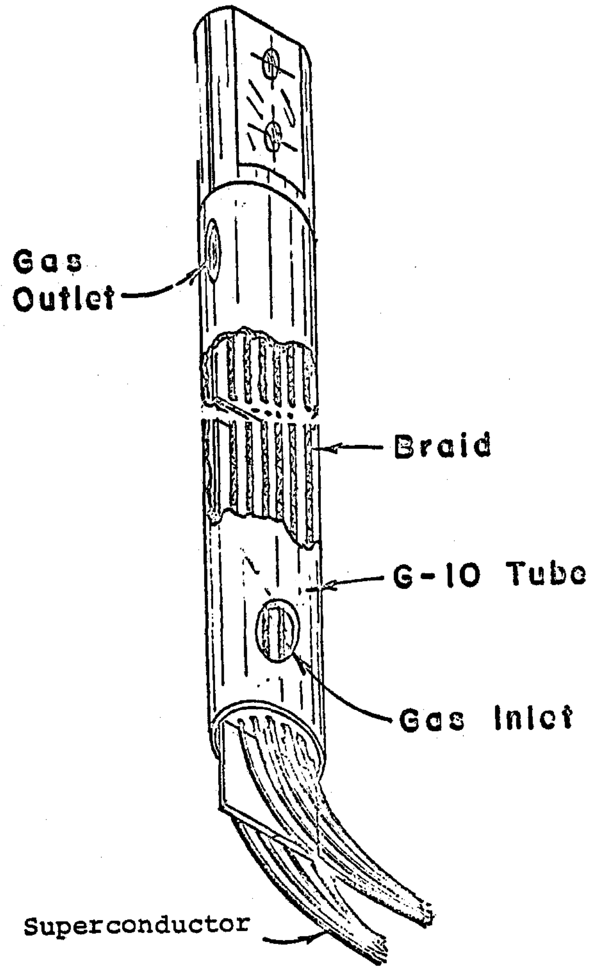

Fig. 2

Gas cooled current lead

3-meter quadrupole in the cryostat. If the cryostat boil-off is 2 or 3 liters/hr and if it contains 500 liters of storage, which is not difficult in large magnets, a weekly transfer of bulk liquid would be adequate.

In order to support the cold mass of these magnets, we have developed a composite column of low heat leak[2]: Figure 4 shows a typical column. A column which will support 2 or 3 metric tons with a safety factor of about 5 will have a heak leak to the 4.2° K region of less than 20 mW. For multiple-column systems one or more of the columns are equipped with flexural hinges top and bottom to allow for differential contraction on cooling.

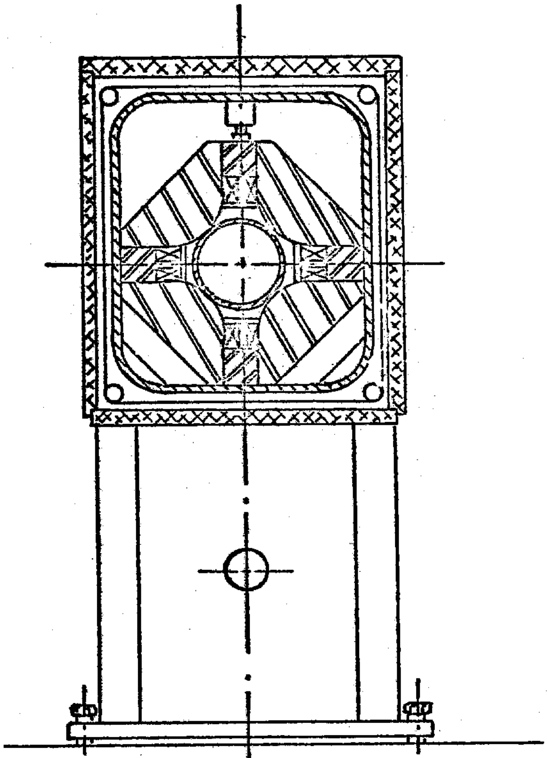

Fig. 3

Cold-iron quadrupole in cryostat

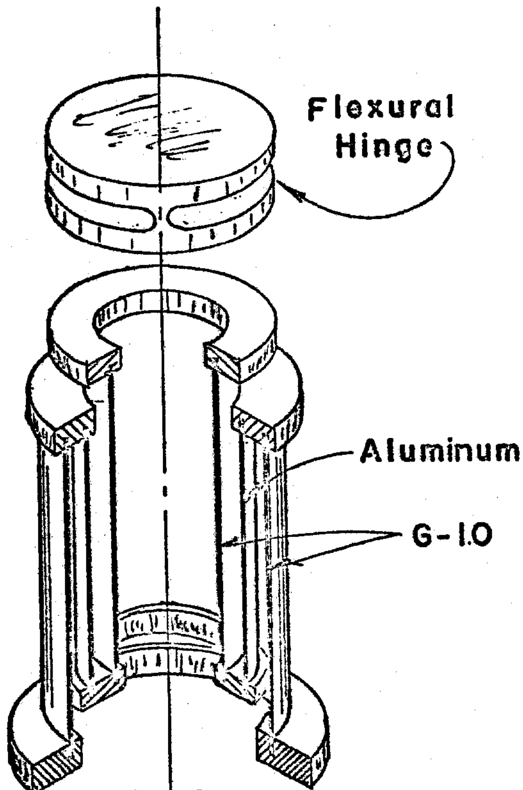

Fig. 4

Composite load bearing column

The operating characterisitcs of the cold-iron quadrupole and analysis dipole are given in Table I. The quadrupole, a 1 H inductance, could be charged without quenching to full field in about ten seconds. It was also operated in a pulsed mode with a 30-second linear rise and a 30-second exponential decay. The measured energy loss agreed well with the losses calculated[3] for the superconductor, substrate and iron. The charging time for the analysis magnet, with an inductance of 10 H, was 10 to 15 minutes. The next generation of magnets of this size for assignment to specific experiments is in design, with construction to start by September, 1972.

TABLE I

Magnet	Field or Gradient	Stored Energy	Operating Current	Total Boil-Off
Cold-iron quadrupole	2 kG/cm	30 kJ	250 A	2 liters/hr
Analysis dipole	18 kG	600 kJ	350 A	3 liters/hr

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*Work performed under auspices of United States Atomic Energy Commission.

1. K. R. Efferson, Rev. Sci. Instr., 38, 1776 (1967).

2. J. R. Heim, Cryogenics, (to be published).

3. W. B. Sampson, et al., Particle Accelerators, 1, 173 (1970).